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Possibility for Artificially Inducing Strong Pitch Angle Diffusion in the Magnetosphere

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14. ABSTRACT
The possibility of strong diffusion by driving intense Alfvenic turbulence in the radiation belts is examined. Intense Alfvenic turbulence is artificially induced by the release of neutral gas in the equatorial plane perpendicular to the ambient magnetic field. The free energy associated with the orbital motion of the released neutral atoms is the energy source of the Alfvenic turbulence. Ions resulting from the photo-ionized neutrals form a ring-type distribution in velocity that is highly unstable to shear Alfven waves near the ion cyclotron harmonics of the released species. The nonlinear evolution of the primary waves leads to redistribution of the wave energy in k-space and to excitation of secondary waves with characteristics appropriate for electron cyclotron resonance with the energetic electrons in the radiation belts that can induce intense pitch angle scattering of the trapped electrons. Release types and requirements to achieve the strong scattering limit are presented.

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Possibility for Artificially Inducing Pitch Angle Diffusion in the Magnetosphere

Turbulence in multi-species plasmas is not only of interest to basic plasma physics but has practical importance because it controls the overall state of space plasmas. It can affect the composition and dynamics of the plasma constituents and hence is a key factor in the determination of space weather an issue of critical importance to the reliability of space assets. Use of active experiments to understand the characteristics of the turbulence is thus an important component in developing a predictive capability for the space environment.

The radiation belt constitutes an important region of the near-Earth plasma environment. The character of the radiation belt is determined by the particles trapped in it. The lifetime of these particles depends on the diffusion processes due to the waves present in this region. We assess the feasibility of artificially inducing intense shear Alfven waves near the ion-cyclotron frequency in a large volume of the near-Earth radiation belt by releasing a neutral gas with low ionization potential, e.g., lithium, perpendicular to the magnetic field and allowing it to photo ionize into a far from equilibrium plasma cloud. This concept is an outgrowth of extensive experimental and theoretical studies, over several decades, of ionizable chemical releases in the magnetosphere [*Brice*, 1970; *Bernhardt et al.*, 1992; *Giles et al.*, 1995] as well as more recent studies of electromagnetic turbulence in a multi-species plasma [*Onishchenko et al.*, 2003; *Ganguli and Rudakov*, 2005; *Rudakov and Ganguli*, 2005]. In particular there has been interest since the 1970's in the use of chemical releases to enhance the growth of waves indigenous to the magnetosphere, such as the whistlers [*Brice and Lucas*, 1971; *Cuperman and Landau*, 1974; *Ganguli et al.*, 1984]. However the novelty of the present scheme is that it envisions designing the local ion distribution through a shaped release of

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neutral gas that draws on the free energy of the artificially created plasma cloud to grow the necessary waves. It has been long predicted by Kennel [1969] that strong diffusion can lead to rapid depletion of the trapped particle. However, the physics of the strong diffusion has not been fully understood or tested. We show that it may be possible to use the neutral release generated large amplitude ion cyclotron waves to induce strong diffusion. In the following we outline an experiment along with global energy estimates that establish its feasibility while deferring a more detailed analysis to a journal article [*Ganguli et al.,* 2007].

We first discuss two distinct mechanisms to deliver the neutral gas into the region of interest in the magnetosphere and highlight their relative advantages and disadvantages. The first is the neutral gas release method in which a ton of vaporized neutral atoms of lithium in gaseous form is released from a set of nozzles perpendicular to the trajectory of a satellite in equatorial orbit at the desired altitude as illustrated in Fig. 1. As the neutral cloud moves along in the orbit its atoms are photo ionized over a characteristic ionization time, T, which depends on the species but in the present paper we will consider lithium. Upon ionization, the lithium ions get attached to a magnetic field line and can no longer move across the field lines. They create a ring distribution in the perpendicular lithium ion velocity that constitutes a highly unstable cloud of lithium plasma, reminiscent of the solar wind-comet interaction [Hizanidis et. al., 1988; *Galeev and Sagdeev*, 1988]. The ring distribution will relax into a broad distribution due to the instability. The distribution could be further isotropized and Maxwelized by lithium-hydrogen collisions. Therefore the density of new born lithium ions which are available with the ring distribution that actively supports the instability is determined by accounting for these

loses [*Ganguli et al.,* 2007]. At any given position the waves generated expend the available free energy in the ring distribution and thereby relaxes it. Waves generated in the equatorial region will be trapped in the magnetic cavity by multiple reflections from the conjugate Buchsbaum points which are encountered as they propagate along the magnetic field lines. Hence, the waves remain in the vicinity of their creation region for a long time. Because the neutral jet moves with the satellite new lithium plasma with ring distribution is continuously generated at different points along the trajectory. The plasma formation time, and hence the instability time scale, at a given point can be controlled by the gas release parameters and nozzle design. Therefore premature relaxation of the ring distribution can be minimized. Detailed analysis of the stability of this multi-ion plasma indicates that a lithium ion density of approximately three to five percent of the background hydrogen density at L = 2 can give rise to high intensity shear Alfven waves near the harmonics of the lithium ion cyclotron frequency [*Ganguli et al.,* 2006; *Sharma and Patel*, 1986]. Thus, the orbital kinetic energy of the lithium can be efficiently converted into electromagnetic waves which can be sustained at least over the duration of the ionization time of the injected neutrals. This is an enormous source of energy, many orders of magnitude greater than the energy that could conceivably be supplied to waves by any electrically-driven antenna in space [*Inan et al.,* 2003]. The neutral lithium atoms are ejected at the satellite speed of $V_s \sim 7$ km/s with energy of 1.75 eV per atom, which corresponds to a total of about 30 GJ for a ton of lithium (i.e., 10^{29} atoms). Since for lithium the ionization time T=3000s, this roughly corresponds to an average power of 10MW for 3000s delivered directly into the region of interest in the magnetosphere. The primary advantage of this method is that it is based on time-tested

and proven technology. However to vaporize 1 ton of lithium approximately 9 tons of heating agent will be required and hence a total payload of 10 tons will be necessary. Although this is not prohibitive and comparable to the NASA/CRRES mission, it is nevertheless a rather large payload to be transported into the orbit.

As an alternative and arguably a more efficient method we suggest utilization of the orbital kinetic energy of the lithium itself for vaporization. This method exploits the thermodynamic property of matter that the specific heat of evaporation decreases as pressure increases. At pressure and temperature exceeding 680 atmospheric pressures and 3200 K the specific evaporation heat reduces to zero. In such a high-pressure environment the energy supplied will be directly converted into internal energy. Such a condition arises in an asteroid-planet impact, and may be replicated by colliding a granular lithium mass moving with velocity V_s with a heavy target moving in a retrograde orbit with the same velocity. At collision the solid lithium will be converted into a hot neutral lithium vapor expanding with an average velocity larger than V_s depending on the lithium and target mass ratio. As the neutral gas expands with high speed, it will rapidly cool down into a collimated lithium cloud. The process of condensation, which could lead to the formation of debris, depends strongly on the impact velocity and vapor density and can be avoided by designing the lithium granule flux to be sufficiently low [*Zel'dovich and Raizer*, 2002].

Consider the collision of a granular lithium mass of 2.5 tons with an aluminum slab of the surface area 30 m^2 and a mass of 7.5 tons used as the heavy target. These masses could be directed against one another in Keplerian orbit in the equatorial plane for a controlled collision in the region of interest. The impact will raise the pressure up to a

million times the atmospheric level and the orbital kinetic energy will be converted into the internal energy of the materials involved. With this internal energy, the lithium gas will expand with an average velocity ~ V_s+2V_{cm}, where V_{cm} is the center of mass velocity of the colliding system. This corresponds to an average energy of approximately 7 eV per atom. As the neutral lithium expands in vacuum the gas cools down and subsequently a collimated neutral lithium vapor flow will expand in the equatorial plane mostly outward under the influence of increased centrifugal force since gas expansion in vacuum proceeds with different velocity for different fluid element. This expansion will create a thin sheet of neutral lithium ions which will photo ionize into a lithium plasma. The heavy aluminum will drop to lower altitudes under the action of gravity. Consequently a lithium plasma cloud will be generated which will seed the electromagnetic turbulence in the way we described earlier. However, the power (~ 100 MW) and energy (~ 300 GJ) released in this case are an order of magnitude larger because the energy of the injected lithium atoms is much larger. Thus, with same mass transported into the orbit it may be possible to deliver about an order of magnitude more energy and power by the impact vaporization method. This obviously is the major advantage of this method. However, the technology involved in the impact vaporization is not fully matured and will require further research.

The free energy introduced by the neutral gas release by either of the methods discussed above will generate Alfvenic turbulence as a consequence of the ring distribution for ions in velocity space generated by photo ionization of the injected neutral jet across the ambient magnetic field. The waves are seeded initially as highly oblique ($k_\perp >> k_\|$, $k_{\perp,\|}$ are wave vectors in perpendicular and parallel to the ambient

magnetic field) shear Alfven waves [McClements et al., 1994] near the harmonics lithium cyclotron frequency which rapidly evolve to the nonlinear stage and coalesce into regular shear Alfven waves with $k_\perp \approx k_\parallel$ [*Voitenko and Goossens*, 2005; *Ganguli et al.,* 2006]. While the initially generated (mother) waves can experience Landau damping, they are negative energy waves and hence the Landau damping does not suppress them. However it can lead to some heating of the thermal electrons. The coalesced (daughter) waves are of long wavelength and are not sensitive to Landau damping. The electric field fluctuations associated with these Alfvenic waves are smaller than the magnetic fluctuations by a factor of $\omega / kc << 1$. These waves are trapped in the magenetospheric cavity formed in a multi-species plasma by reflection from conjugate Buchsbaum points in the two hemispheres and can remain there for a long time in a manner similar to that discussed by *Roux et al*. [1984]. The frequency range and wave vectors of these waves can resonate with the ambient relativistic electrons. A consequence of this will be marked enhancement in the precipitation of the trapped energetic electrons due to increased pitch angle scattering. We use this property to estimate the energy budget involved in the experiment and to determine the diagnostic feasibility of the scheme.

The lifetime of a trapped electron, τ, is given by [*Kennel and Petschek,* 1966],

$$\tau = (\gamma_R / |\Omega_e|)(B_0 / B_1)^2 \ln(2 / e\theta), \tag{1}$$

where γ_R is the relativistic factor and θ is the pitch angle. For a 2 MeV electron $\gamma_R = 5$. Also at L = 2, $B_0 = 0.04G$, i.e., $\Omega_e = 7\times10^5$ rad/s, and $W_0 = B_0^2 / 8\pi = 0.63\times10^{-5} J / m^3$. Using Eq. (1) and $\ln(2 / e\theta) \sim 1$ we can estimate that significant precipitation will require wave magnetic field energy density supplied by the turbulence of the order of,

$$E_F = \frac{B_1^2}{8\pi} = \frac{1}{\tau}\frac{\gamma_R}{\Omega_e} W_0 \,. \tag{2}$$

The turbulence is sustained over the ionization time, so we use trapped electron lifetime $\tau \sim 3 \times 10^3$ s to be comparable to the turbulence lifetime. This provides an estimate of the necessary field energy density to be,

$$E_F = 0.27 \times 10^{-13} \text{ J/m}^3. \tag{3}$$

Since the total wave energy density for the shear Alfven waves is related to the field energy density by $W = E_F\left(1 + k_z^2 c^2 / \omega_{pH}^2\right)$, and $k_z^2 c^2 / \omega_{pH}^2 = 9$ for the resonant waves [*Ganguli et al.,* 2007] we have,

$$W = 0.3 \times 10^{-12} J / m^3 \,. \tag{4}$$

Assuming that the turbulence is filled in a volume, $V \sim 10^{21} m^3$, between L = 1.5 and 2.5, we estimate the total energy to be delivered into the turbulence to be,

$$E = WV \approx 3 \times 10^8 J \,. \tag{5}$$

For a total energy introduced by the traditional chemical release method of $3 \times 10^{10} J$, the efficiency of conversion of the released energy into the required turbulence energy should be 1% or higher. If necessary this threshold can be further improved by releasing larger amounts of lithium through multiple release events. However if the impact vaporization method is adopted then with only one release event an efficiency threshold of 0.1% is required. It should also be noted that the injected energy in the magnetosphere available for turbulence is orders of magnitude larger than the ambient wave energy since the amplitude of the background fluctuations is of the order of a pico tesla. Therefore the turbulence is likely to be of high intensity. This implies that the proposed scheme of

inducing high intensity Alfvenic turbulence in a large volume in the near-Earth plasma environment is quite feasible.

Since the threshold for conversion efficiency is only about 1% it is quite possible that a larger fraction of the injected energy may find its way into the turbulence and lead to the onset of strong diffusion [Kennel, 1969]. Thus, the onset (or the lack) of strong diffusion can be used as a diagnostic for the transport of energy in the turbulence and hence a measure for the conversion efficiency of the process. As described by Kennel [1969] the strong diffusion limit is based on the population of the loss cone. In the weak diffusion limit the loss cone is basically empty with the exception of the region near its boundary. In this case the distribution function increases exponentially from pitch angles $\theta = 0$ to $\theta = \theta_0$ where θ_0 is the half-angle of the equatorial loss cone. In this limit the particle lifetime is proportional to the inverse of the diffusion coefficient ($1/D_{\theta\theta}$). In the strong diffusion limit the distribution function remains almost isotropic and the particle lifetime is independent of the magnitude of $D_{\theta\theta}$ but sensitive to the loss cone angle. The particle lifetime approaches a minimum value given by $\tau_m \approx \pi/\omega_b \sin^2\theta_0$ where ω_b is the particle's energy dependent bounce frequency. According to the criteria discussed by Kennel [1969] and refined later by Lyons [1973] and Schulz [1974] the strong diffusion limit occurs when $D_{\theta\theta} > 1/\tau_m$. For the vicinity of L ≈ 2 the condition corresponds to wave energy density in the resonant region larger or equal than 10^{-11} J/m^3, which is many orders larger in magnitude than the naturally occurring background energy density. This energy density may be achieved by one ton of neutral lithium release if the efficiency of conversion is higher so that a larger fraction of the injected energy is deposited into the

waves in a smaller volume. In this way the strong diffusion limit may be accessed under controlled conditions.

In summary we conclude that conversion of orbital kinetic energy of matter into free energy for designing and seeding specific turbulence over a large volume in the near-Earth region offers an efficient method for generating enormous amounts of electromagnetic power directly in the space environment. A consequence of this will be the precipitation of the relativistic trapped electrons from a large volume of the inner radiation belt within hours which could be readily measured and correlated to the turbulence as a diagnostic of the turbulence intensity. The energy density of the induced waves can be increased to meet the onset condition for strong diffusion by reducing the volume of release if the conversion efficiency is higher. This represents an excellent method for using the near-Earth space environment as a test bed for investigating the role of turbulence in defining the plasma state of this region. A more detailed analysis describing the linear and nonlinear wave properties and pitch angle scattering is given in *Ganguli et al.* [2007].

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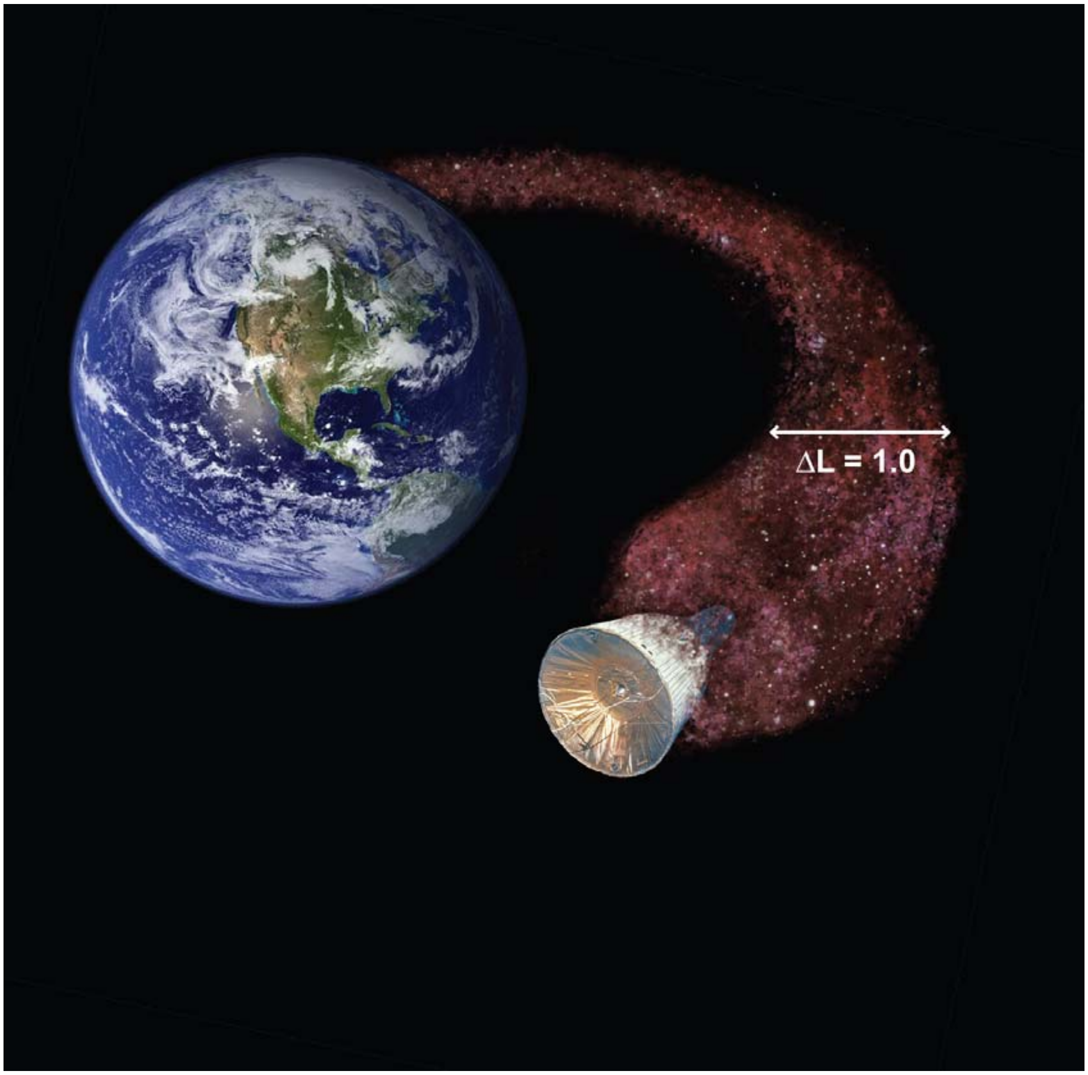
FIGURE CAPTION

Fig. 1. A schematic of the neutral lithium gas injection. The gas is released radially normal to the satellite trajectory in the Earth's equatorial plane where the ambient magnetic field is perpendicular to the satellite trajectory. With a release speed of $V_R \sim 1$ km/s it is possible to create a lithium cloud of width $\Delta L \approx 1$ (i.e., 6000 km) which can be photo-ionized into a plasma cloud.


ΔL = 1.0